

# Low Energy Nuclear Recoil Ionization Yield and SuperCDMS Sensitivity

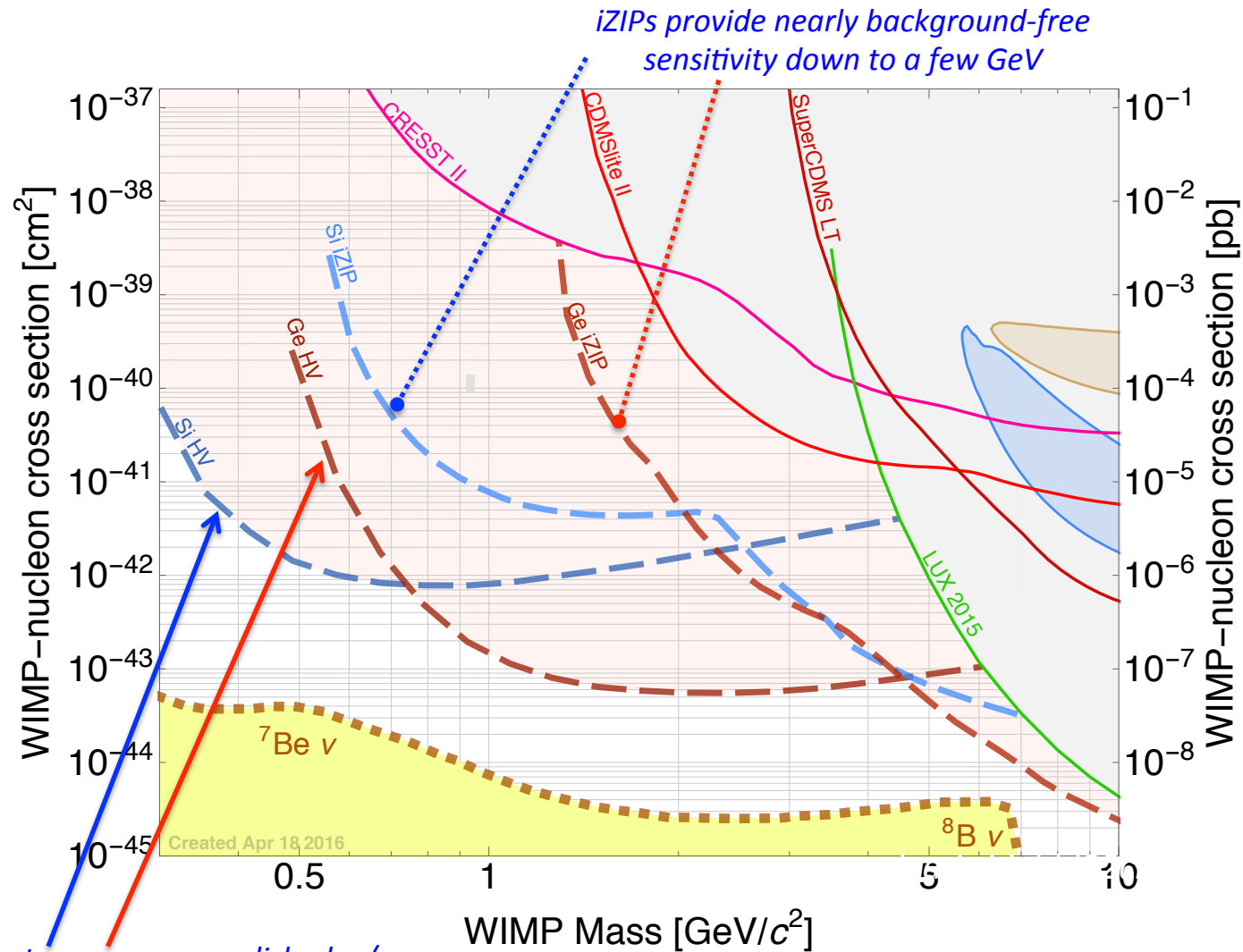
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# SuperCDMS SNOLAB Projections



*Reach at lowest masses accomplished w/  
CDMSlite (HV) style detectors w/ 10 eV  
phonon resolution and  $< 100 \text{ eV}_{nr}$  threshold*

# Review of recoil energy calculation

*In SuperCDMS detectors, recoil energy is measured from total phonon energy after correcting for Neganov-Luke phonons:*

$$E_{\text{recoil}} = \frac{E_{\text{total}}}{1 + Y_{\text{ionization}} * eV_{\text{bias}} / \epsilon}$$

~4V for iZIP  
~70V for CDMSlite

energy for e/h pair = 3 eV in Ge

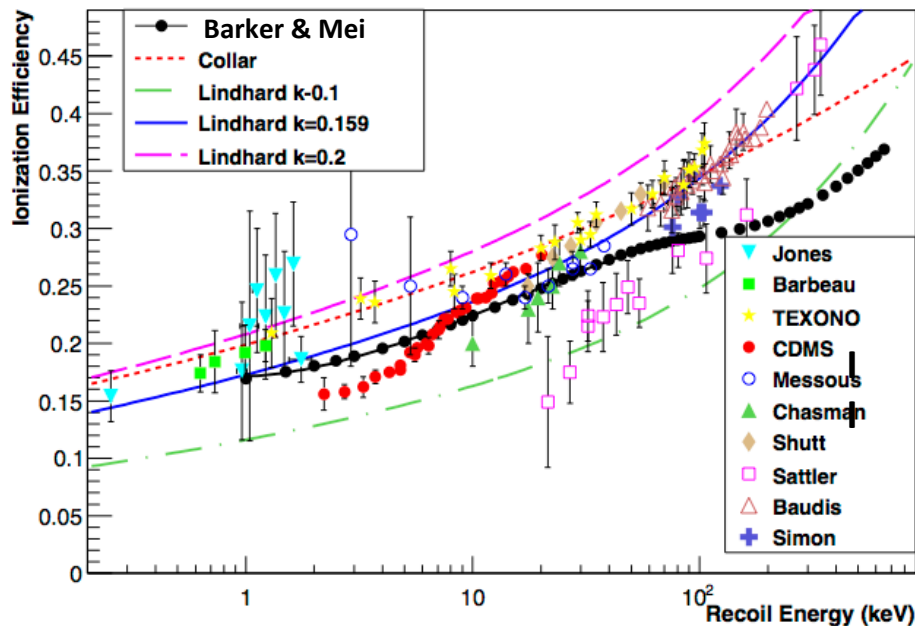
*Accurate recoil energy measurement requires knowledge of ionization yield (quenching factor) for given recoil type*

$$Y_{\text{ionization}} = E_{\text{ion}} / E_{\text{recoil}}$$

$Y_{\text{ionization}}$  is measured directly with iZIPs on an event-by-event basis during exposure to gamma and neutron sources. But this is not the case for HV detectors.  $Y_{\text{ionization}}$  must be determined independently in order to extract  $E_{\text{recoil}}$

# Current status on ionization yields

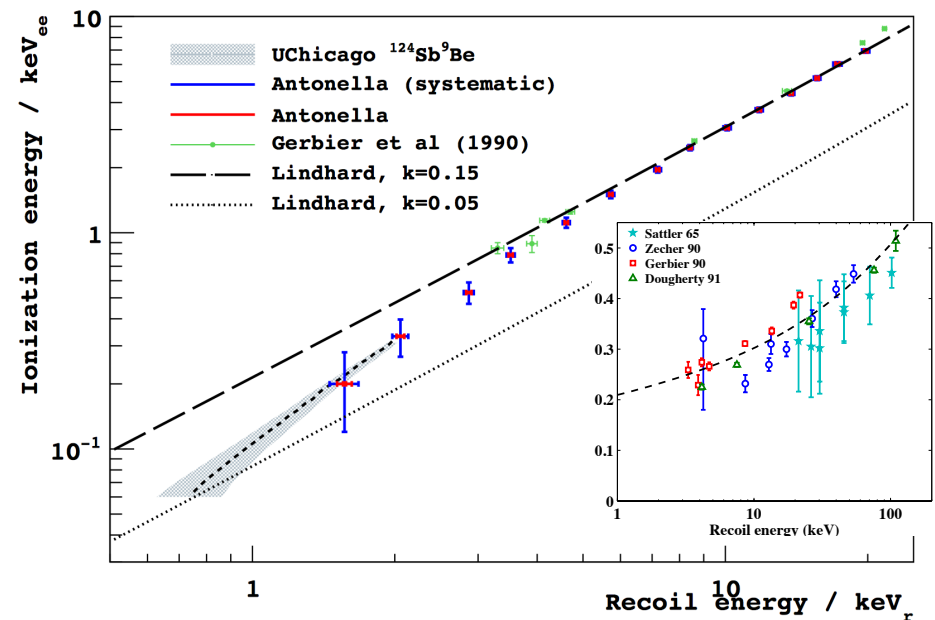
## Germanium



Note sensitivities on previous slide assumed 40 eV ionization threshold and that ionization yield follows Lindhard down to that point.

*In addition to how much the yield differs from Lindhard, at some point we expect a physical turnoff in ionization yield. Where this cutoff is can have large implications.*

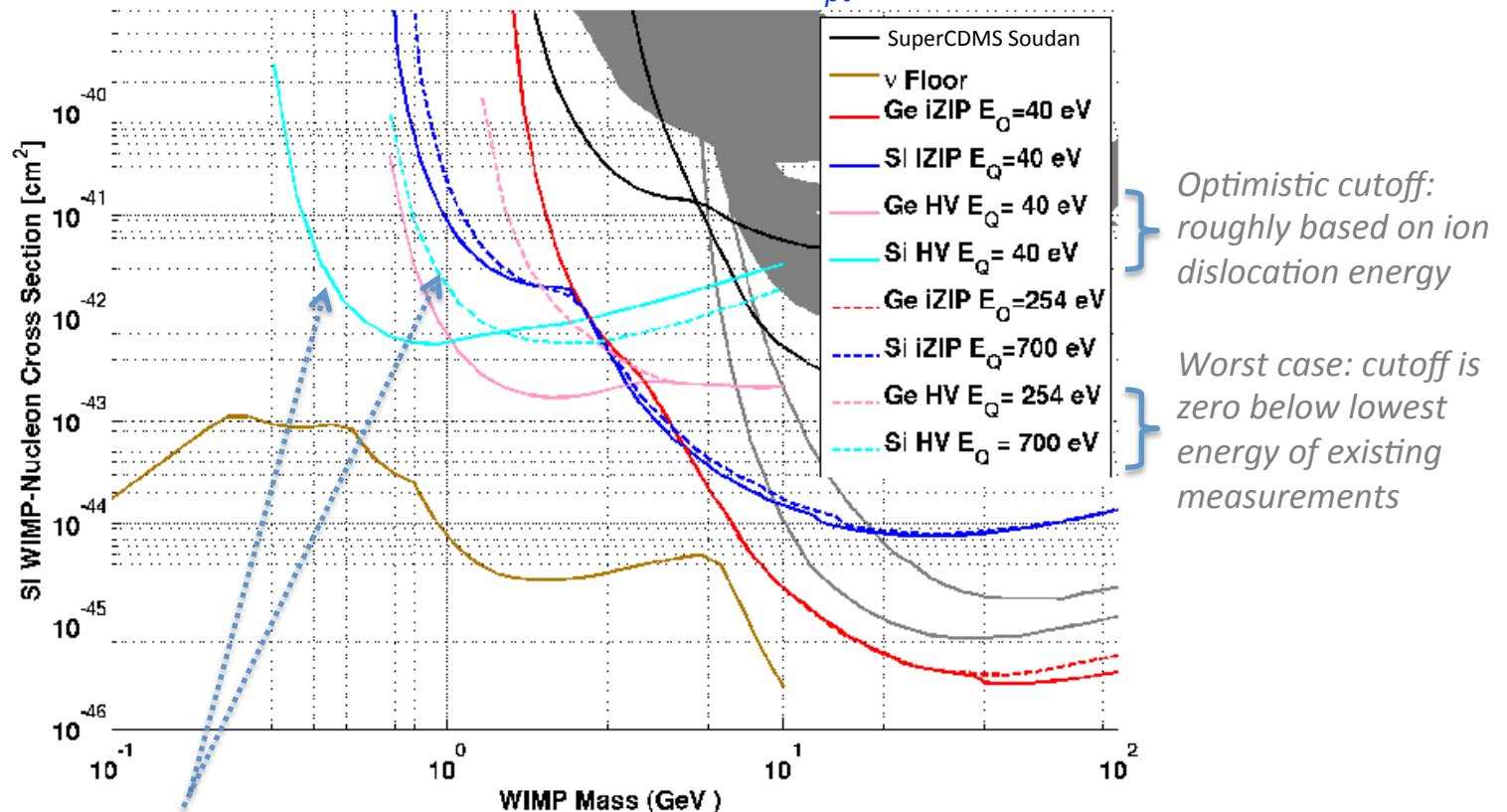
## Silicon



# Example effects of ionization yield cutoff on SNOLAB sensitivities

Baseline resolution case:  $\sigma_{pt} = 50(25)$  eV for Ge (Si), HV = 50V

Hardware threshold assumed to be  $7 \cdot \sigma_{pt} = 350(175)$  eV

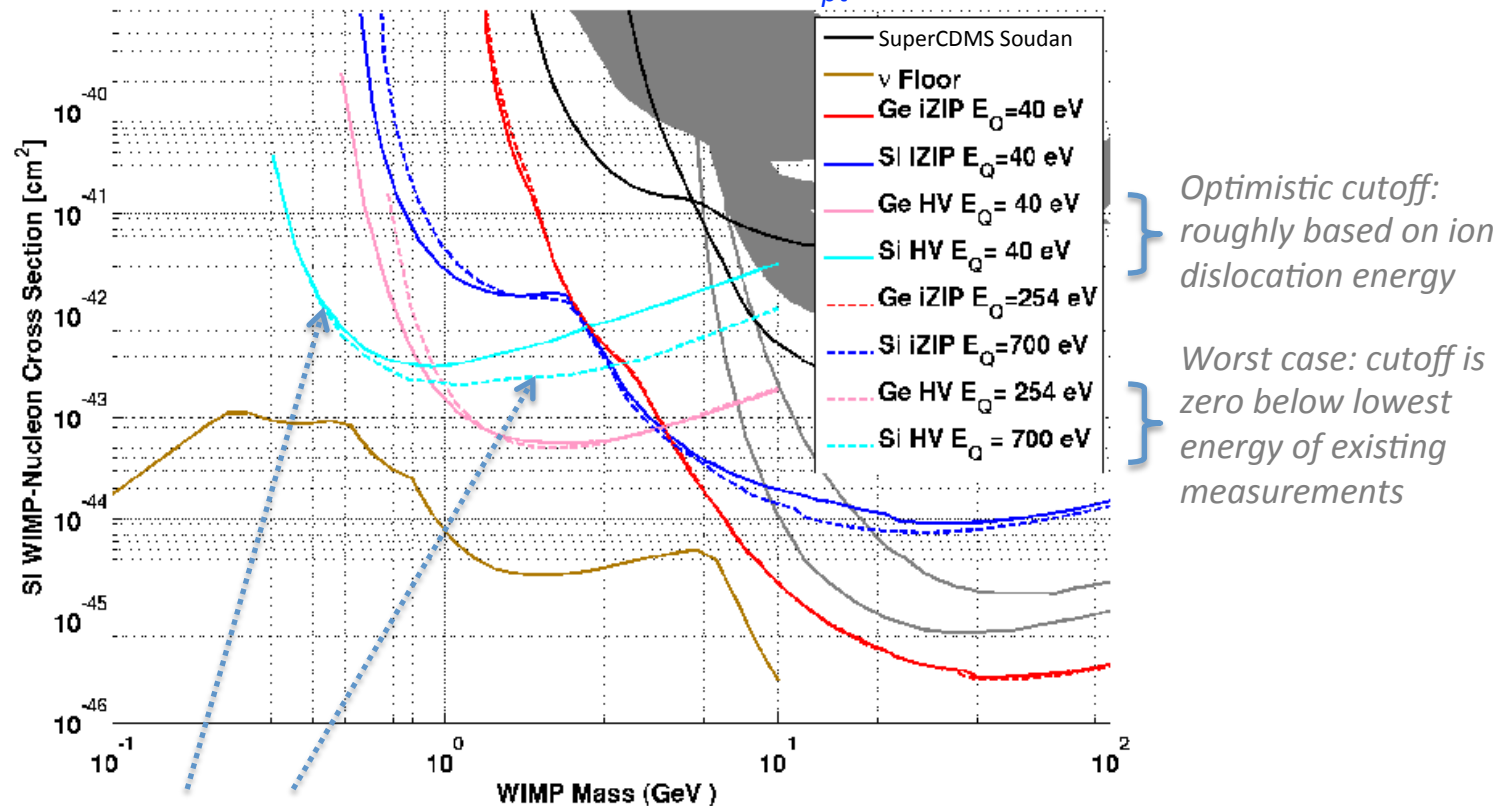


Here, ionization threshold makes a large difference in sensitivity for HV detectors. The difference arises from hardware threshold being below (optimistic case) versus above (worst case) the ionization threshold and hence where Luke phonons exist to amplify the NR signal.

# Example effects of ionization yield cutoff on SNOLAB sensitivities

Goal resolution case:  $\sigma_{pt} = 10(5)$  eV for Ge (Si), HV = 100 V

Hardware threshold assumed to be  $7 \cdot \sigma_{pt} = 50(35)$  eV



Here, effect is less severe bc the hardware threshold is so low it's already below the ionization threshold in both scenarios (for Si) so there's no difference in NR thresholds between optimistic and worse case. In fact, Luke gain is no longer useful for reducing threshold, instead use it to tune what ER backgrounds wind up in the signal NR region.

# A few other caveats:

1. Several effects are experimentally degenerate with ionization yield in SuperCDMS detectors. In other words,  $\epsilon$  and “1” are not really constants at all energies, voltages and detectors.

$$E_{\text{recoil}} = \frac{E_{\text{total}}}{1 + Y_{\text{ionization}} * eV_{\text{bias}} / \epsilon}$$

These will vary with field strength, phonon sensor design and crystal purity. To reduce systematics, important to verify energy scale in the same type of detectors used for WIMP search

*2. The intrinsic spread in ionization yield matters as well as the mean in determining experimental sensitivities. The fano factor will affect this and so far, we don't have a good understanding of fano factor for nuclear recoils in Ge or Si.*

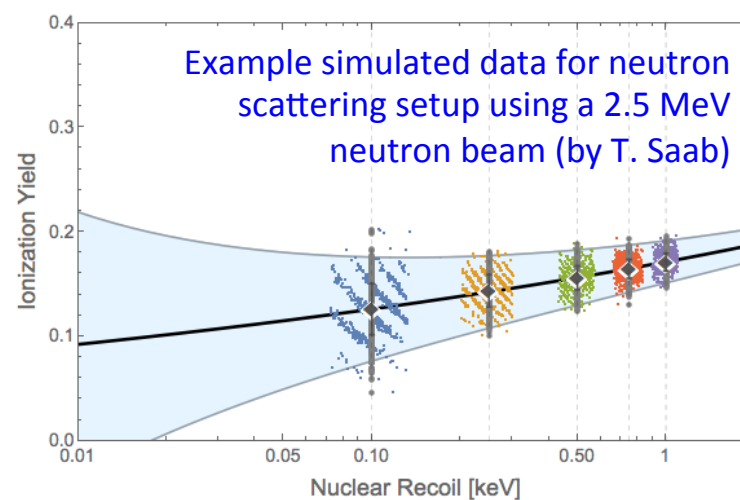
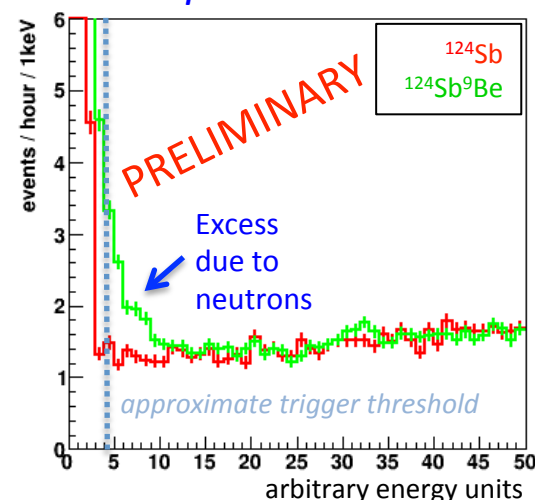
# Measuring the energy scale for SuperCDMS

SuperCDMS is pursuing multiple energy scale calibration measurements:

1. *In the near term we have taken data at Soudan with two photoneutron source SbBe and YBe. Will provide calibration CDMSlite down to at least 1 keV*
2. *Plans over the next 3 years include nuclear recoil calibration down to at least 100 eV using a neutron scattering setup and prototype HV detectors. With 10 eV resolution, we think we can constrain fano factor as well.*

*Telling you more about each of these efforts would take up talks of there own so sorry I won't go into much more detail here (!)*

*Soudan photoneutron data*





# Summary

*G2 SuperCDMS sensitivity depends on knowing the detector responses to nuclear recoils, especially for HV detectors*

Effects of ionization yield, and especially its cutoff value, can be subtle with SuperCDMS HV detectors; depends on the thresholds are achieved by the technology

With optimal resolutions for our HV detectors ( $<10$  eV), Neganov-Luke gain is no longer a tool to reach low thresholds, but instead a way to tune what backgrounds overlap with our signal region

Effects degenerate with ionization yield imply its important to do the calibrations with the same types of detectors at the same voltages as the WIMP search

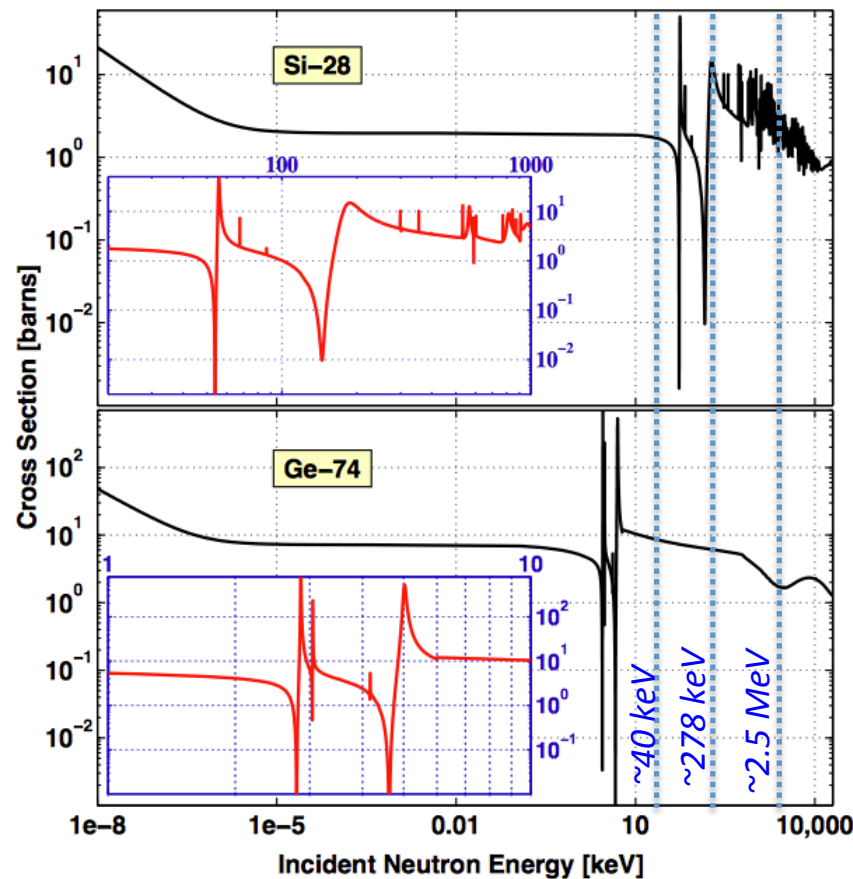
*Nuclear recoil calibration of SuperCDMS Soudan and SuperCDMS SNOLAB detectors are in the works, stay tuned!*

# Backup slides

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# Elastic scattering cross sections

*From Ray Bunker's thesis (appendix E.4)*

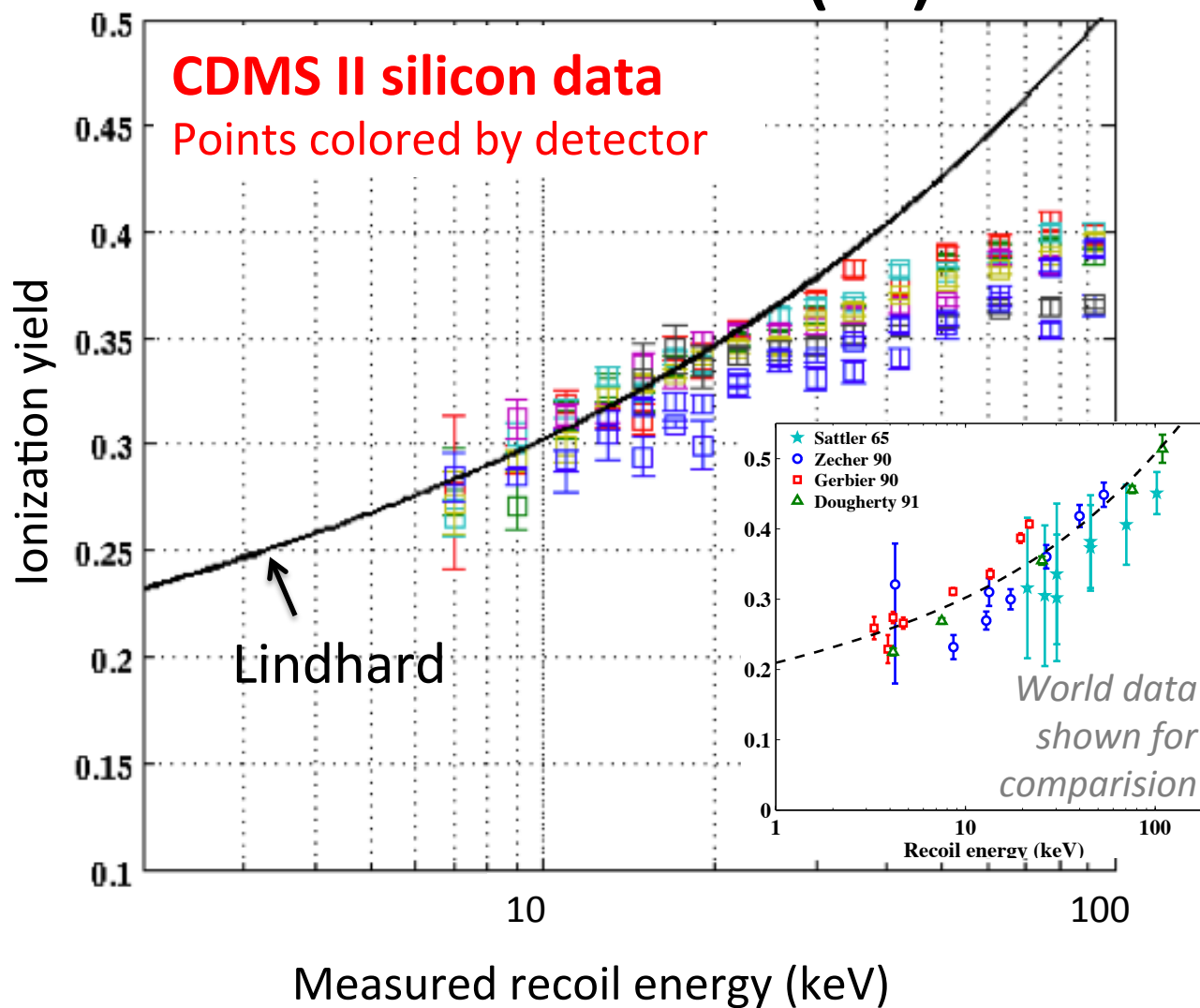


Dotted lines indicate several energies of interest:

- 40 keV =  $\sim$  TUNL min energy with (p,Li) beam
- 278 keV =  $\sim$  backscattered DD energy from deuterium target
- 2.5 MeV =  $\sim$  energy of straight DD beam

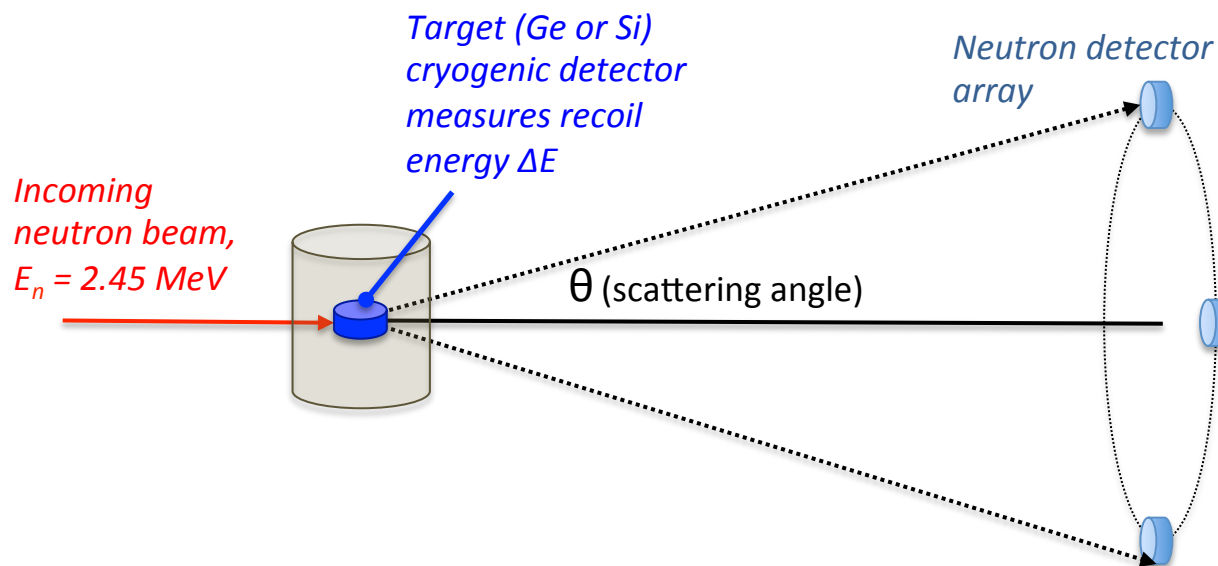
Figure E.3: Cross sections for neutrons to elastically scatter from Si (top) and Ge (bottom) nuclear targets as a function of incident neutron energy. Zoomed in views of the resonant regions are provided in the insets. Cross sections interpolated from data found in the JENDL database [609].

# How does CDMS II yield compare to Lindhard (Si)?



# Recoil Measurement from Scattering

A straightforward way to calibrate the nuclear recoil energy scale is to use a neutron scattering setup

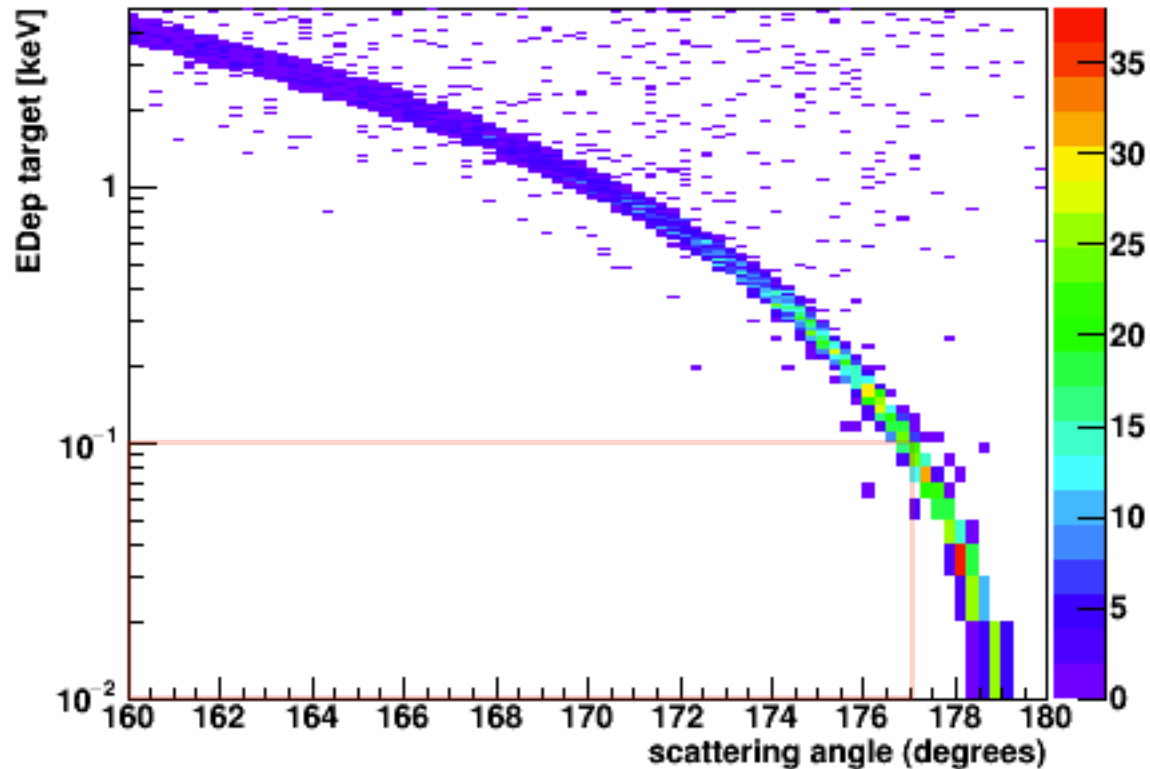


$$\Delta E = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \left( \frac{M_T}{M_n} + \sin^2 \theta - (\cos \theta) \sqrt{\left( \frac{M_T}{M_n} \right)^2 - \sin^2 \theta} \right)$$

*Precise knowledge of the scattering angle and incident (monoenergetic) neutron beam will yield the recoil energy in the calibration detector*

# 2.5 MeV incoming n on Ge

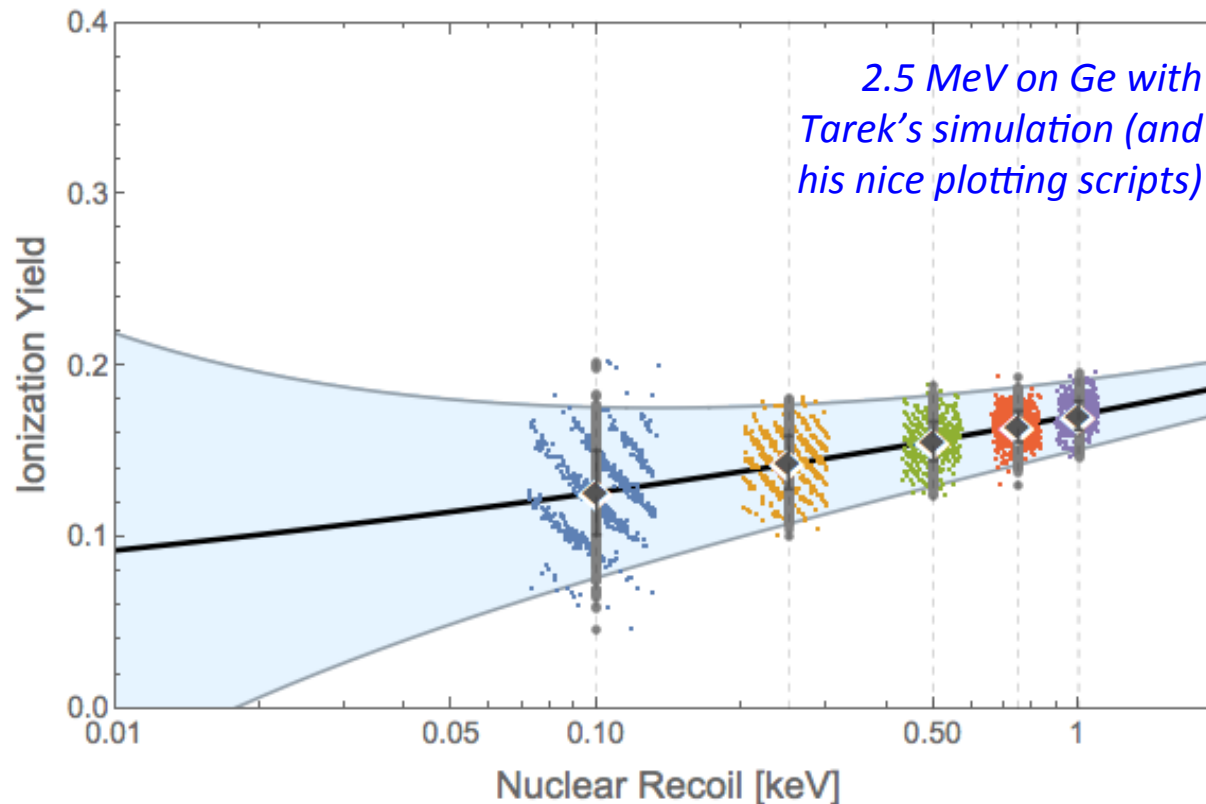
*Smearing from angular and detector resolution not applied*



n interaction length  $\sim 6.5$  cm  
0.5 $^\circ$  uncertainty at 100 eV yields  $\sim 30\%$  energy scale uncertainty

# 2.5 MeV incoming n on Ge (Yield)

*Previous slides don't include statistical fluctuations from finite e/h pair generation. Below is (idealized) yield vs recoil energy for a D-D beam with secondary detectors that subtend  $1^\circ$ , and a 10 eV Ge detector resolution.*

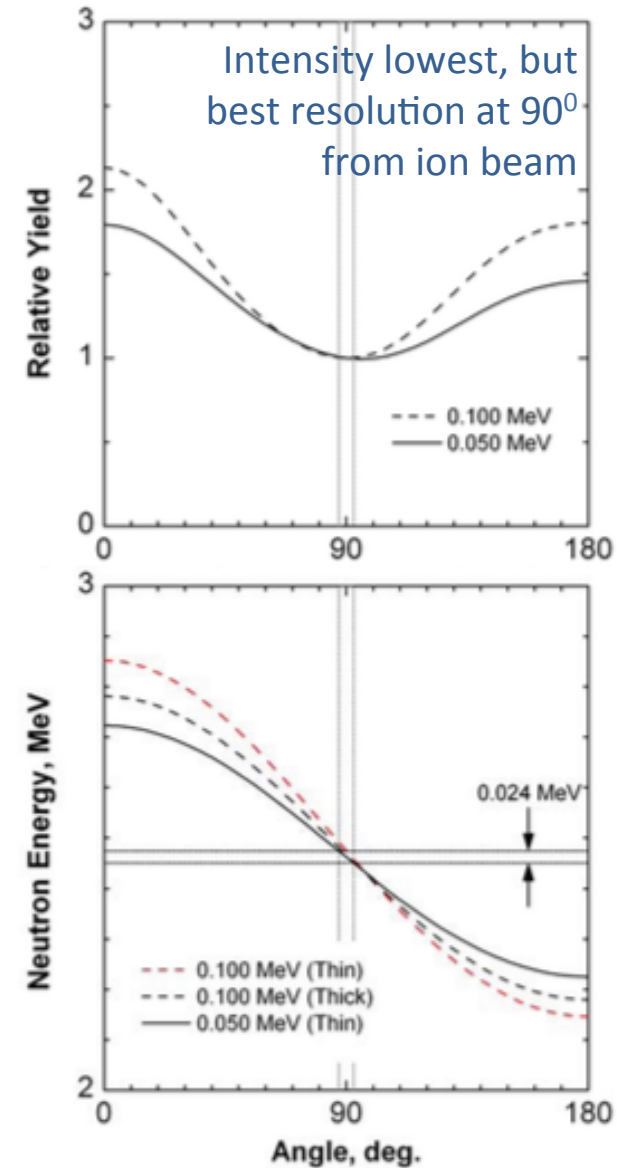
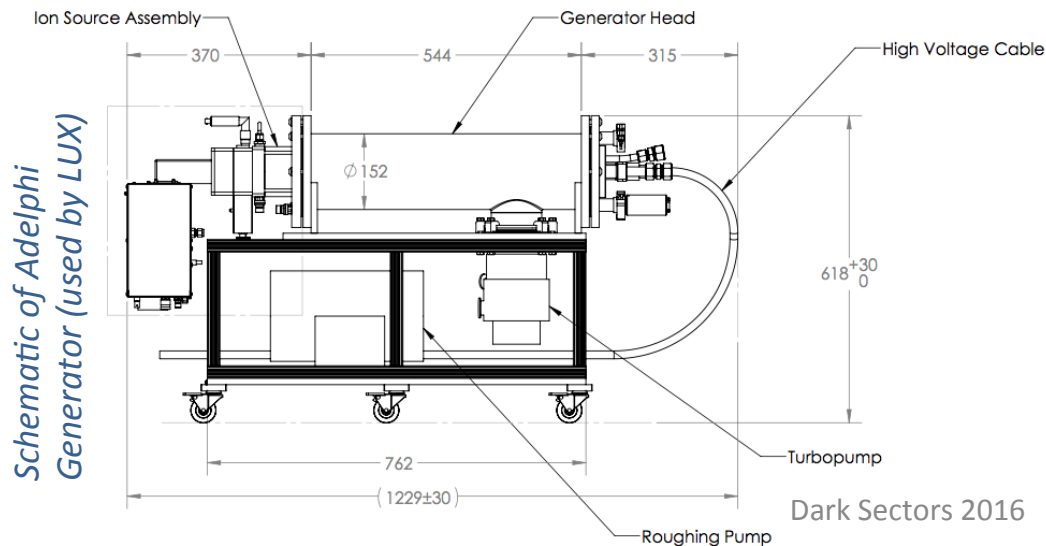


In total phonon energy vs recoil energy plane its possible to unfold individual e/h peaks visible here →adequate detector and angular resolution also provides understanding of nuclear recoil fano factor



# DD generator Basics

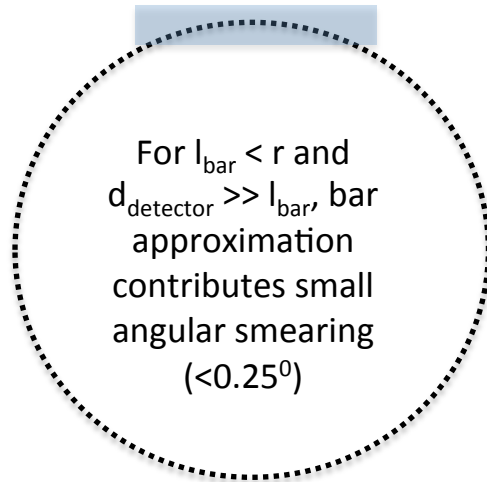
- **Reaction:**  $D + D \rightarrow {}^3\text{He} + n$ ,  $Q = 3.36 \text{ MeV}$
- Energy, intensity and beam purity depend mildly on emission angle
- Acceleration potentials of 100-300 kV produce neutrons 2-3 MeV at  $1\text{e}6\text{-}1\text{e}10 \text{ n/s}$  into  $4\pi$
- Most generators can be pulsed (min  $\sim 10 \text{ us}$ ); measurement may be clean enough to do without
- Compact, portable generators widely available (used in field by oil industry).



Chichester, Johnson and Seabury: <http://dx.doi.org/10.1063/1.3586154>

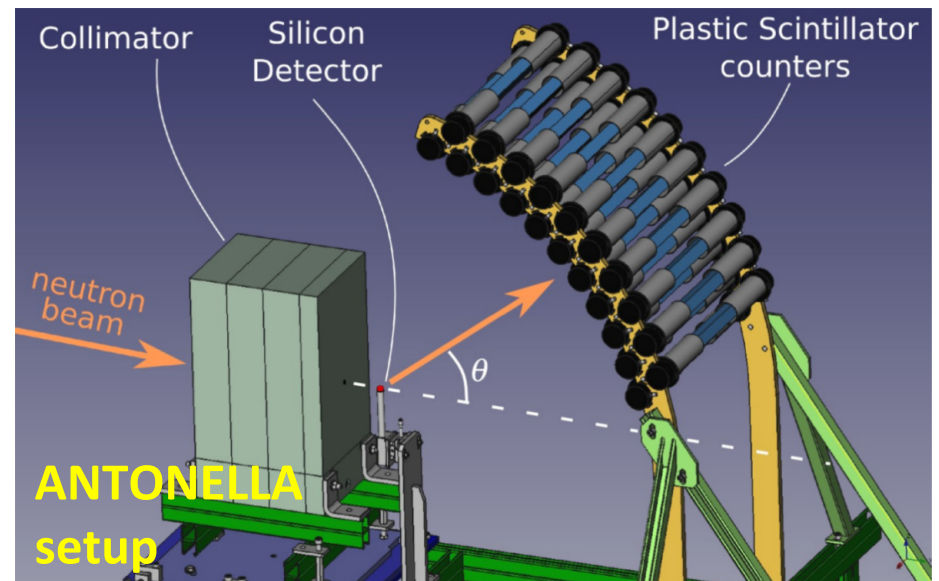
# Secondary detector array

- Requires dedicated fine-grained neutron detector array covering scattering angles of interest from  $2^\circ$  to  $10^\circ$  (corresponds to energies from 100 eV to 1 keV)
- Ideally detectors contribute  $< 0.25^\circ$  angular resolution to scattering angle measurement; this can be achieved with  $\sim 1\text{cm}$  detector at a distance of 1.5 m.
- Maximizing angular coverage while minimizing channels is key to design
- Detection threshold must be reasonably low (50-100 keV *for neutrons*)
- Timing and PSD help (nanosecond timing resolutions not needed)



**One possibility:** borrowing an idea from ANTONELLA, use bars of plastic scintillator to approximate arc of a circle.

*ANTONELLA array also available for use and can be used to measure recoil energies of a few keV with 2.5 MeV beam*



# Hamamatsu R760 phototubes

*Major cost for a fine-grained array with up to several dozen channels is in the instrumentation and readout! (few K per channel)*

- Thank to Erik Ramberg and the now defunct SELEX experiment, we have been given a long-term loan of ~32 Hamamatsu R760 phototubes (yay!). These tubes have active photocathode diameter of 1cm and already instrumented with bases.
- Investigating possibility to use Mu2e boards (designed at Fermilab by Sten Hansen and colleagues) to readout the array. Adapters to use the boards with PMT's already exist
- NOvA style plastic scintillator can be had for free with the sizes we want, although for not much money we can also buy high-quality EJ-200.

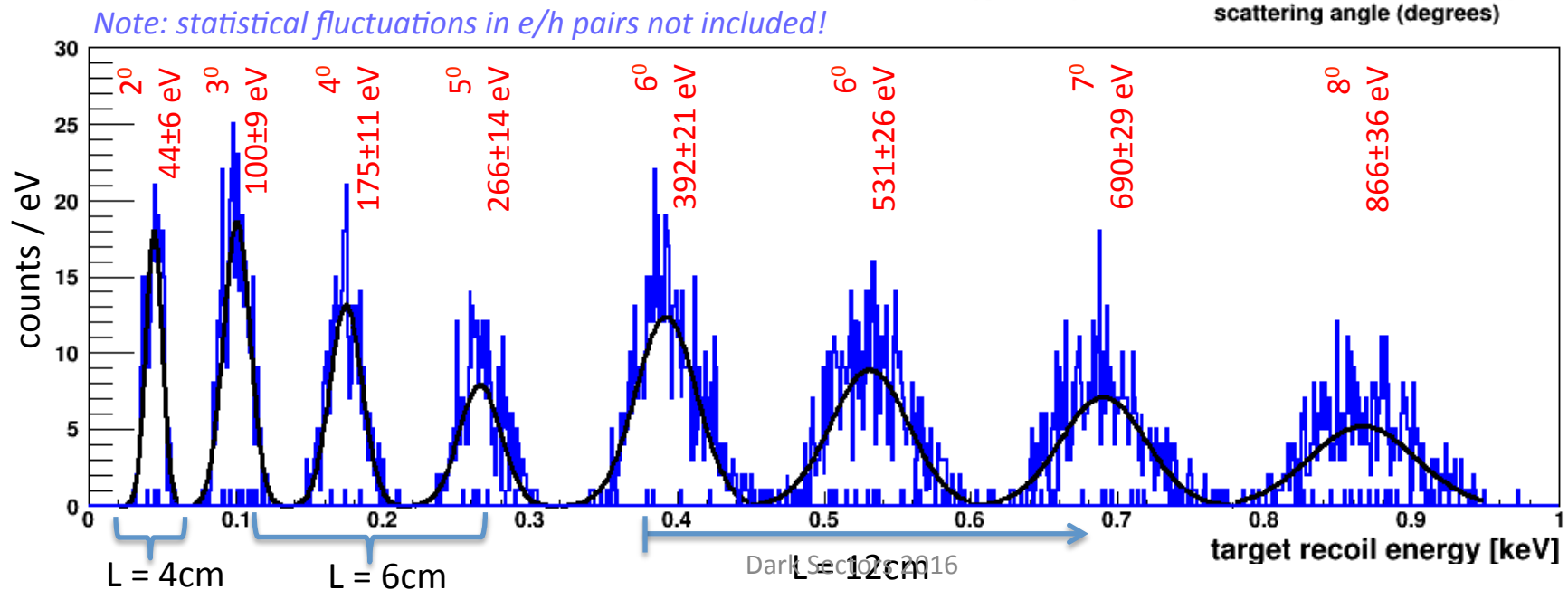
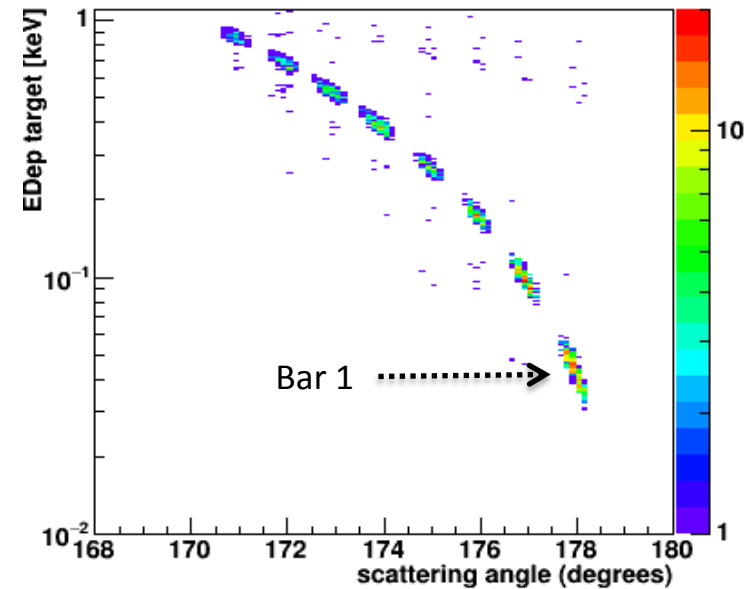


*With these pieces, the cost of the fine-grained neutron array would be almost negligible (and gives Fermilab/Northwestern summer students lots of fun things to do)*

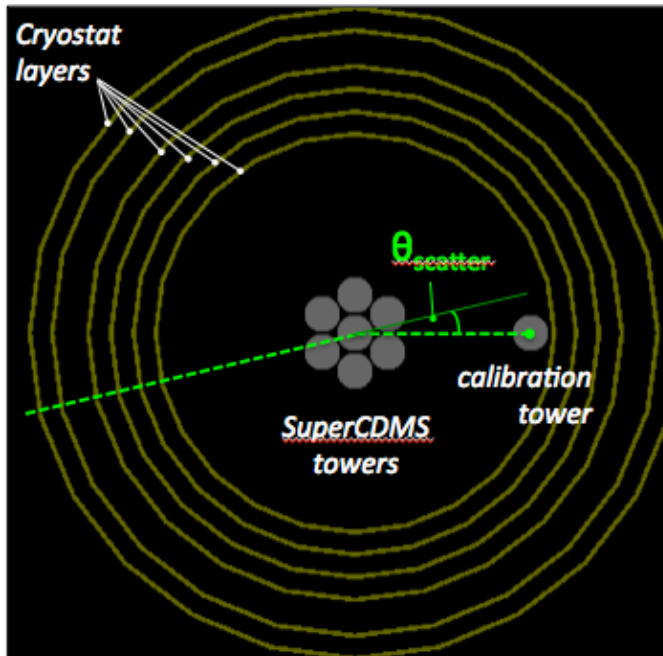
# Neutron bar simulation

## Geant4 simulation:

- 8 scint bars spaced from  $2^{\circ}$  to  $9^{\circ}$ , at distances of 1.5-1.9 m
- Primary target is Ge (1cmx1cm)
- Scint bars are 1cmx1cmxL where L = 4, 6 or 12 cm
- Simulation gives idea of scattering rate and resolution smearing introduced by this geometric arrangement



# In situ calibration at SNOLAB



- Monoenergetic beam of neutrons produced by a D-D generator (such as an Adelphi DD108)
- Aim beam at central array of detectors and detect scatter with calibration tower offset from detector stack (3/8" copper cryostat layers)

- Precise position information of iZIPs allows for small angle reconstruction and thus allows to reconstruct down to very small energies.
- Position resolution studied in advance at a test facility.
- Precision of 5-10% may be achieved down to intended trigger thresholds (100 eV)

